

## Hot Air Stratification of Ceiling Air Supply in a Large Space Building

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**Abstract:** The effects of different states of air supply and airflow patterns on temperature gradient distribution are calculated and analyzed with the help of FFSV3.0 software, using the LB models and LES and RANS methods. An experimental study with upper supply and upper return air flow was performed in normal airflow room. The results were compared with numerical simulation results and were found to agree well. Information on delaminating laws, and measurements of the relationship of delaminating heights and air supply temperature and velocity is also presented. According to the simulation results, a formula that avoids hot air delaminating in ceiling air supply is derived, which can guide engineering design.

**Keywords:** air flow; air conditioning; hot air delaminating; numerical simulation

### 1 PREFACE

Air conditioning systems with air supply temperature difference are frequently used in large space buildings. Because the characteristic parameters such as temperature, density and turbulent intensity are different between cold and hot airflow, there exists heat and mass transfer between them after their encounter. At the same time they repel each other and the hot airflow frequently floats on the upper layer, which results in energy waste and the bad effect of air conditioning. Delaminating phenomena of cold and hot airflow can also cause air blow-by of each layer and upper hot and lower cold in some high commercial buildings. Therefore, it is necessary to study the laws of cool and hot air delaminating, mixing and repellency, which has the

significant scientific and application value in perfecting air flow

designs in air conditioning of large space buildings.

In the air conditioning buildings, most of the actual airflow is turbulence. Therefore the main object in the research of temperature lamination phenomenon of indoor airflow is turbulence. Because of the complexity of actual air flow, the turbulence theory and the computation technology have all not achieved the level to massively solve the problem of fluid mechanics in the actual project at present. As a result, now the traditional methods are mainly used actually. In the recent 20 years, how to solve the turbulence problem in the engineering adopting turbulence theory is studying both domestic and abroad. Turbulence models (RANS), especially two-equation model, already become the universal used methods in the computation of indoor flow fields. In this paper, flow fields distributions at different parameters in ceiling air supply are studied; the relationship between the heights of delaminating and air supply temperature and velocity is analyzed with the help of the software of FFSV3.0, using LES and RANS methods. The numerical simulation results are compared with the experimental study.

### 2 TURBULENCE MODELS IN DESCRIBING HOT AIR DELAMINATING PHENOMENON OF INDOOR AIR FLOW

In the turbulence models, the standard k- $\epsilon$  model developed earlier and gained the broadest application in the indoor airflow calculation<sup>[1]</sup>. The low Re

number  $k-\varepsilon$  model is used to describe the influence of the buoyancy to the flow in the field, by introducing drag coefficient in the standard  $k-\varepsilon$  model. To different low Re number  $k-\varepsilon$  model, their drag coefficient expression are different. The commonly used low Re number  $k-\varepsilon$  models include the LB model (Lam and Bremhorst, 1981)<sup>[2, 3]</sup>, NT model (Nagano and Tagawa, 1990)<sup>[2]</sup>, improved  $k-\varepsilon$  model (S Murakami, 1992)<sup>[4]</sup>, MKC model (S Murakami, 1994)<sup>[4, 5]</sup> etc. Chen et al simulated indoor air flow on the natural convection with several kinds of low Re number  $k-\varepsilon$  models in 1995. It was discovered that the computed results obtained by the LB model agreed best with the experimental data and also did well in the research of analyzing temperature delaminating phenomenon<sup>[2]</sup>. In addition, the high-accuracy aeolotropism turbulence model such as DSM (Differential Stress Model)<sup>[6]</sup>, because of large computation, has not become the conventional model in the indoor thermal environment analysis, and yet should be studied further<sup>[7]</sup>. Compared with  $k-\varepsilon$  the model, ASM (Algebraic Stress Model) has large computation and high accuracy because of using the Rodi assumption to simplify the DSM, However, compared with the direct numerical simulation, the accuracy of large eddy simulation is almost high, but its computation greatly reduced actually. So its application prospect is wider than DNS in the analysis of indoor thermal environment<sup>[5, 8-10]</sup>.

### 3 COMPARISONS OF ANALYSIS METHODS OF TEMPERATURE LAMINATION

Currently, the analysis methods of temperature lamination are mainly CFD method and the simplified method of energy analyses and CFD method is regarded as a reliable and higher accuracy method in theory. RANS method and LES method have been adopted respectively to analyze temperature lamination and the basic laws of delaminating have been obtained. Numerical simulation can rather comprehensively figure out every kinds of flow field information when boundary conditions have been given. Therefore it is commonly used for computing the indoor temperature field, velocity field as well as concentration field of harmful gas. And it can compute indoor thermal

environment of the structures in use or under construction. Simultaneously, its results can be tested by model experiment. It has advantages of speediness, economy and convenience etc.

The simplified method of energy analyses is mainly used to calculate the indoor thermal environment influenced by outdoor climatic conditions greatly, which is namely the non-stable state indoor calculation. Because it is a macro-calculation model of the total temperature field, the treating of boundary condition do not such strict like numerical simulation. Due to its strong dependence to test data, the application scope of the simplified method of energy analyses is only limited in indoor thermal environment calculations of the buildings in use<sup>[11]</sup>.

To air flow vertical temperature lamination influenced by outdoor climatic conditions small, the flows which exist temperature stratification are mostly low Reynolds number flows. Seen through the analysis and comparison, it is relatively suitable to use the LB model in the RANS model. Therefore, in this paper, effects of different states of air supply and airflow patterns on temperature gradient distribution are calculated and analyzed using LES and RANS method. Also two simulation methods are compared with each other.

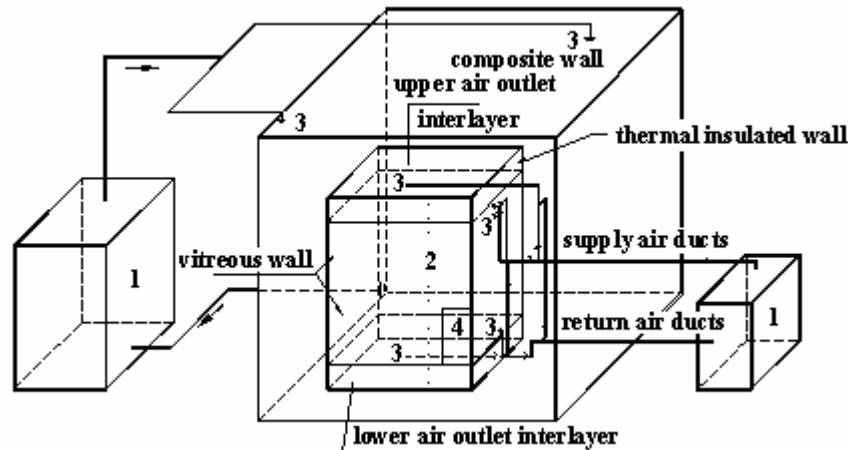
### 4 EXPERIMENTAL SYSTEM OF NORMAL AIR FLOW ROOM

In this paper, an experimental study with upper supply and upper return air flow is carried on in normal airflow room with the size  $3\text{m} \times 3\text{m} \times 3\text{m}$ . The size of supply-air outlet and return-air outlet are both  $0.23\text{m} \times 0.23\text{m}$ , see Fig. 1. The air outlet at  $Z=3\text{m}$  in the XOY plane is supply-air outlet and that at  $X=0$  in the YOZ plane is return-air outlet. The experimental system is mainly made up by the following several sections:

- 1) Hot-wire anemometer IFA300 and TSI Model 1128 equipped with one-hole to three-hole probes, which can measure the magnitude and direction of indoor airflow velocity;
- 2) Particle image velocimetry;
- 3) KL2000 intelligent temperature and humidity tour inspection system;

4) Infrared thermometer ST20, ST60, temperature meter RHTF-1, intelligent temperature recorder RHLOG and other temperature log equipments, can detect wall temperature and air temperature and record by itself, and also can measure and save the data regularly.

As the advanced flow test methods at present, hot-wire anemometer and particle image velocimetry are very effectively used for proving the indoor airflow. Especially to large eddy simulation, they have obvious superiority.



□ air-conditioning unit □ normal air flow room (3m×3m×3m) □ air outlet □ door

**Fig. 1 The structure of normal air flow room**

## 5 CFD SIMULATIONS

In order to correspond with the experiment, prove and analyze the results of numerical calculation. In this paper, upper supply and upper return air flow is studied regarding normal air flow room with the size 3m×3m×3m as a calculation model.

The Calculation indicates that the grid division influences not only the computational rate, but also the convergence of the calculation results. In RANS, by using the grid of 30×30×30 and after 20 hours' iteration time, it achieves convergence and the result reaches the expected convergent accuracy. In the paper, the grid used in LES is 72×70×70, which is finer than that in RANS.

The supply-air outlet of simulated object locates at the ceiling. In the situation of the same supply-air height, the temperature difference is changed into 10°, 15°, 20°, 25° and 30° separately. And air velocity is changed between 0.5m/s and 2.0m/s at the same time; the interval is 0.1m/s. Flow fields under various situations are simulated by using simulation software of FFSV3.0. During the calculation, the absolute value of the difference between supply-air temperature and boundary temperature is regarded as

the qualitative temperature. The average value of supply-air temperature and boundary temperature is considered as the reference temperature. And air velocity is adopted as the qualitative velocity.

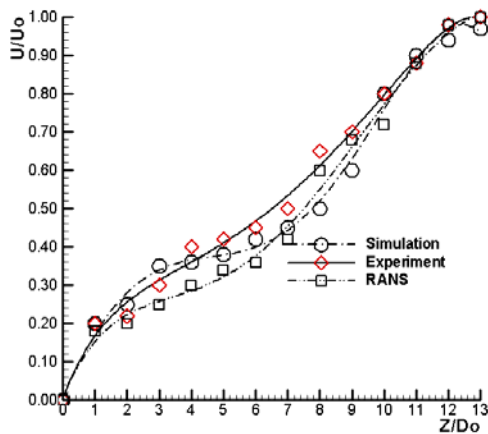
## 6 DISCIPLINARIAN ANALYSIS OF HOT AIR DELAMINATING PHENOMENON OF UPPER SUPPLY AND UPPER RETURN AIR CONDITIONING FLOW

### 6.1 Calculation Results and Analysis

#### 6.1.1 Comparison among k - ε model, large eddy simulation and experiment

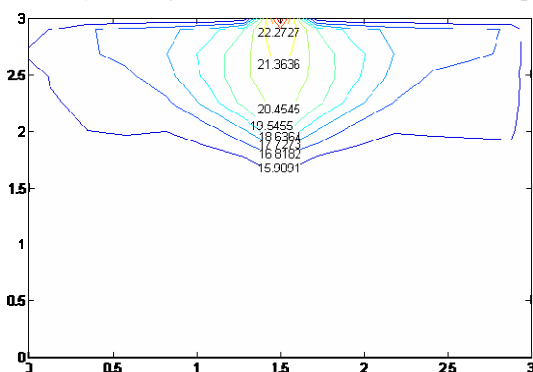
Fig. 2 is the comparison of the attenuation of the jet average velocity between large eddy simulation and RANS simulation. Fig. 3 is the contrast of the attenuation of average temperature. It can be seen that the results of LES, RANS and the experiment are consistent with each other. The maximal error between LES velocity simulation and the test is 13.3% and its mean square deviation is 0.06. The maximal error between RANS and the test is 14.2% and the mean square deviation is 0.11. The maximal error of the attenuation of the jet axial temperature between large eddy simulation and the test is 12.3%.

The maximal error of temperature decay between RANS simulation and the test is 15.5%. The compared results indicate that the theoretic accuracy of large eddy simulation is higher than that of



**Fig. 2 The comparison of the attenuation of the jet average velocity**

When  $\Delta T$  is  $10^\circ\text{C}$  and air velocity is 0.5 m/s, the temperature contours at the center axial plane is shown in Fig. 4. From the figure, it can be seen that there appears obviously temperature delaminating phenomenon. The temperature in the whole working place is all below  $16^\circ\text{C}$ . As the velocity rising to 0.8m/s, the temperature contours obviously moves down to the height around 1 meter (Fig. 5). With the velocity rising to 1.2m/s further, the temperature



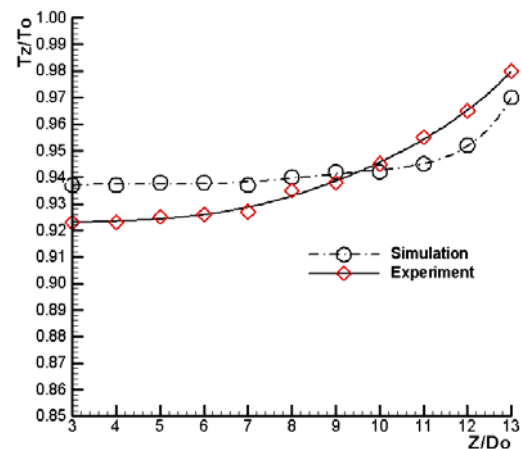
**Fig. 4 Temperature distributions at  $\Delta T=10^\circ\text{C}$ ,  $v=0.5\text{m/s}$**

### 6.1.3 Changes of flow fields as temperature difference of supply-air increasing

Fig. 8 and Fig. 9 are numerical simulation results in the conditions of same velocity and different temperature difference. And they primarily indicate the influential laws of supply-air temperature difference on flow field. When  $\Delta T$  is  $15^\circ\text{C}$  and air

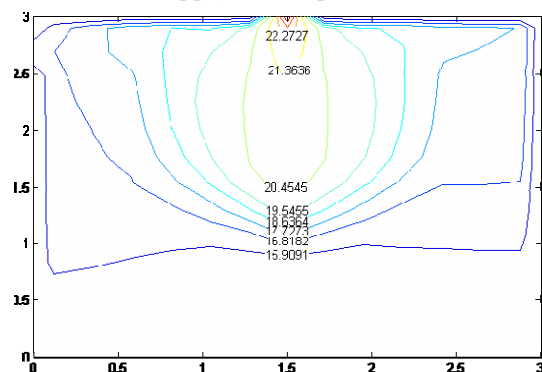
turbulence model. Consequently, LES is adopted in the formal simulation in the paper.

### 6.1.2 Changes of flow fields while air velocity increasing



**Fig. 3 The comparison of the attenuation of the jet average temperature**

contours moves down further and temperature delaminating phenomena disappears. However, the temperature is not enough even yet (Fig. 6); as the velocity rising to 1.5m/s, the temperature of working place basically reaches  $18^\circ\text{C}$  which is satisfied with the design requirements (Fig. 7). According to the above analysis, it can be concluded that different air velocity will lead to different height of delaminating at the same supply-air temperature.

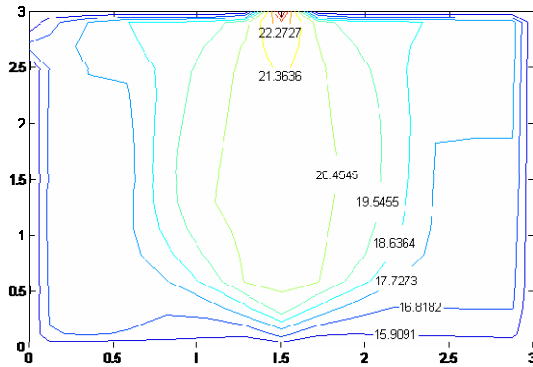


**Fig. 5 Temperature distributions at  $\Delta T=10^\circ\text{C}$ ,  $v=0.8\text{m/s}$**

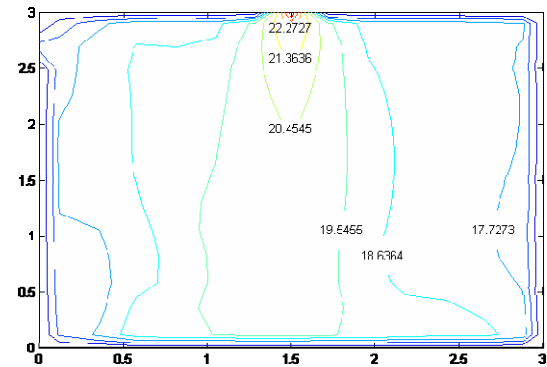
velocity is 0.5 m/s, the temperature contours at the center axial plane is shown in Fig. 8. At this moment, the maximum temperature of working place under 2 meters is  $15.2^\circ\text{C}$ . Compared with Fig. 4, it can be seen from Fig. 8 that axial temperature at 2m height reduces nearly  $3^\circ\text{C}$  and it can be seen from Fig. 9 that axial temperature reduces nearly  $7^\circ\text{C}$ . It indicates that

the buoyancy received by jet increase and the temperature delaminating phenomena is distinct rapidly with the increase of temperature difference. When temperature difference rises to  $30^{\circ}\text{C}$ , the ability of jet to overcome the buoyancy moving down descend further and the maximum temperature of

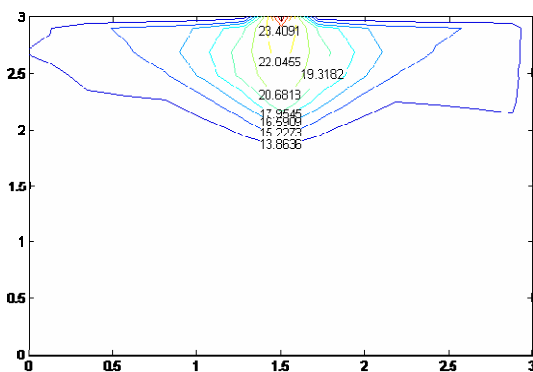
working place under 2m is only  $8^{\circ}\text{C}$ . That is to say, air supply has not distinct significance to working place at this moment. Thus it can be seen, temperature difference has great influence on delaminating phenomena.



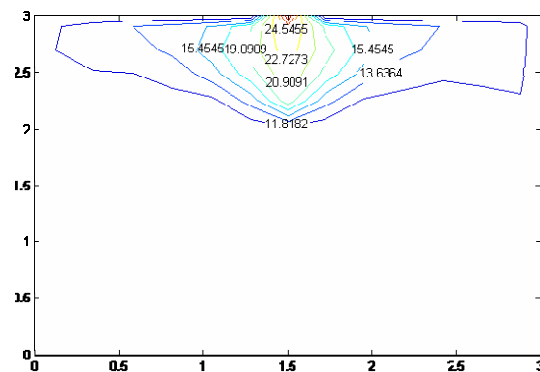
**Fig. 6 Temperature distributions**  
at  $\Delta T=10^{\circ}\text{C}$ ,  $v=1.2\text{m/s}$



**Fig.7 Temperature distributions**  
at  $\Delta T=10^{\circ}\text{C}$ ,  $v=1.5\text{m/s}$



**Fig. 8 Temperature distributions**  
at  $\Delta T=15^{\circ}\text{C}$ ,  $v=0.5\text{m/s}$



**Fig. 9 Temperature distributions**  
at  $\Delta T=20^{\circ}\text{C}$ ,  $v=0.5\text{m/s}$

## 6.2 Analysis of Temperature Delaminating Law

### (1) Delaminating standard

In the air conditioning room, human body would have obvious cold drafts feelings when indoor temperature is below  $18^{\circ}\text{C}$ . Therefore, air-conditioning temperature is generally designed at  $18^{\circ}\text{C}$  in winter. It is generally considered that the height of indoor working place is within the range 2 meters above the ground. In normal case, when the average temperature of working place reaches  $18^{\circ}\text{C}$  and has certain evenness, it is thought to reach expected effects. On the contrary, if average temperature can not reach  $18^{\circ}\text{C}$ , air-conditioning is regarded to be ineffective. So, in the paper, the temperature contours height at  $18^{\circ}\text{C}$  is considered as the standard for judging temperature delaminating.

And as the standard for judging temperature delaminating, this simple judgment standard is easy to operate.

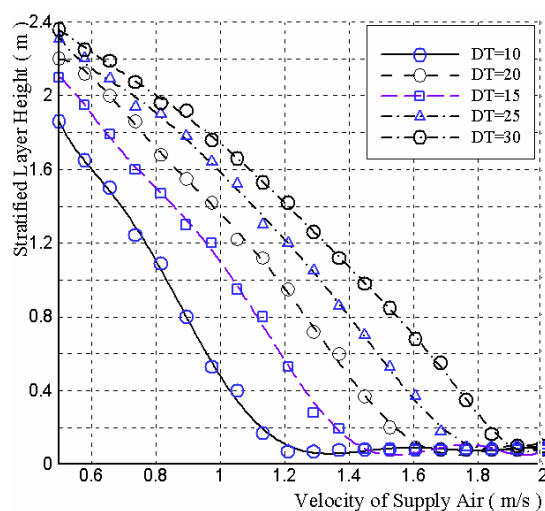
### (2) Delaminating law

As the above mentioned, delaminating height reduces following the velocity increasing at the same temperature difference; and increases following the temperature difference increasing at the same velocity. In order to intuitionistically reflect the influence of temperature difference and velocity on the delaminating height, it is shown in Fig. 10. The data were collected from a large number of simulation results. And this figure is the graph of temperature contours height at  $18^{\circ}\text{C}$  changing along with air velocity and temperature, fitted by numerical simulation. It is known from Fig. 10 that temperature

delaminating height reduces gradually following air velocity increasing in the conditions of different temperature difference. At the same height, the larger the temperature difference is, the bigger the air velocity needed for overcoming temperature delaminating is. This agrees with the practice. When temperature difference is relatively small, such as 10℃ or 15℃, the curve slope decreases. When air velocity is greater than certain value, temperature delaminating height becomes very small and goes to be invariable at the same temperature difference. Here, it can be judged that temperature delaminating phenomenon disappears. And this velocity is defined as the transitional velocity that occur temperature delaminating phenomenon. The transitional velocity will be different at different temperature difference. Based on data fitting, the changes of transitional air velocity, to avoid temperature delaminating, along with temperature difference can be given by the following relation:

$$U_0 = 0.034 \Delta T + 0.88 \quad (1)$$

Where:  $\Delta T$  is the temperature difference between supply-air temperature and wall temperature.



**Fig. 10 The influences of temperature difference and air velocity change on delaminating**

Based on the formula (1), the transitional velocity for avoiding delaminating phenomena can be gained at the air distribution of upper supply and upper return and different temperature difference. Taking into account of the non-uniformity of the temperature in working place, the transitional

velocity  $U_t$  to avoid delaminating phenomena can be defined as the following relation:

$$U_t \geq K \times U_0 \quad (2)$$

Where: K value is taken in the range of 1.4 to 1.5.

### 6.3 Error Analysis

It can be known from the above-mentioned compared results, there are certain differences between simulation and test, and the reasons are given as follow:

- (1) In the process of computing, flow field is assumed to be invariable, but in fact it can not be stable because of the influence of fan and outdoor flow field in the test;
- (2) The forms of air-inlet have certain influence on indoor flow fields;
- (3) Due to experimental airflow is turbulence, there are differences between the time value read by IFA300 and the time-averaged concept of numerical simulation;
- (4) During temperature measurement, reading error appears because temperature sensor exists delay time;
- (5) The car has certain influence on indoor flow fields and the swing of the standing bar can cause position error of testing dot while moving the probes.

### 7. CONCLUSIONS

Based on the above analysis and test, some conclusions can be gained as follows:

- (1) The numerical simulation results agree well with the experiment data. It means that the computation program adopted in this paper, especially the large eddy simulation, can perfectly simulate indoor airflow fields in the case of temperature lamination;
- (2) Temperature and air velocity are important factors that influence the temperature delaminating height. At the same air temperature difference, the temperature delaminating height decreases along with air velocity increasing; in order to reach the same temperature delaminating height, the higher the temperature difference is, the larger the air velocity is. According to numbers of numerical simulation, the

formulas (seeing from formula 1 and formula 2) that avoid hot air delaminating in ceiling air supply are presented, which can guide the air conditioning engineering design.

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